

Thermal Properties of LARP Type Nb₃Sn Superconducting Magnet Coil Electrical Insulation in Pressurized Superfluid Helium

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Abstract The development of new generation, high-performance devices, such as MRI scanners or high-energy accelerators, (may be attributed to the use of) Nb₃Sn based superconducting (SC) magnets, which are characterized by their ability to produce much higher magnetic fields than the presently used NbTi-based magnets. Due to the wind-and-react technology of the production of Nb₃Sn magnets, new methods and materials for the magnet coil electrical insulation are required. The proper design of SC magnets demands the characterization of thermal properties of the new insulation materials, inter alia, in superfluid helium conditions. This paper provides experimental data of the thermal conductivity and Kapitza resistance for S-glass fiber reinforced ceramic-epoxy (LARP type) electrical insulation, measured in pressurized (at 1 bar pressure) superfluid helium in a temperature range of 1.50–2.00 K.

Keywords Kapitza resistance · Thermal conductivity · Superfluid helium · Nb₃Sn magnets electric insulation

1 Introduction

One of the key elements of the superconducting magnets is magnet coil electrical insulation. The insulation material, aside from high electrical strength, should also be characterized by potentially high mechanical strength in order to withstand the Lorentz forces occurring in the powered magnets. It should also possess the high capacity to transfer

heat from the magnet coil to the magnet coolant. Those requirements are fully complied by Kapton polyimide commonly used in the NbTi magnets. Nevertheless, due to the application temperature of Kapton at up to 400 °C, this material is not suitable for the Nb₃Sn magnet wind-and-react production technique, which requires a heat treatment of approximately 650 °C. Therefore, for the further development of Nb₃Sn-based technology, new materials and methods for magnet coil electrical insulation are required.

Within the European Coordination for Accelerator Research and Development (EuCARD) program, four potential materials for Nb₃Sn magnets coil electrical insulation have been selected and thermally characterized in pressurized superfluid helium (HeIIp) conditions. The thermal conductivity and Kapitza resistance for S-glass fiber reinforced epoxies (RAL Mix 71, RAL Mix 237), as well as for cyanate ester epoxy resin (CE epoxy) have already been published [1, 2]. Here, the data for S-glass-ceramic-epoxy laminate (LARP type) are presented.

2 Test Procedure

2.1 Test Method Principle

The thermal properties of the tested material have been determined by the so-called “drum method”, as schematically presented in Fig. 1. In this method, the tested material sample with surface A [m²] and thickness L [m] separates a space into two volumes, both filled with HeIIp. The temperature of the first volume T_b [K] is controlled at a constant value, while in the second volume, a constant heat Q_s [W] is dissipated and the temperature T_i [K] of this volume is measured.

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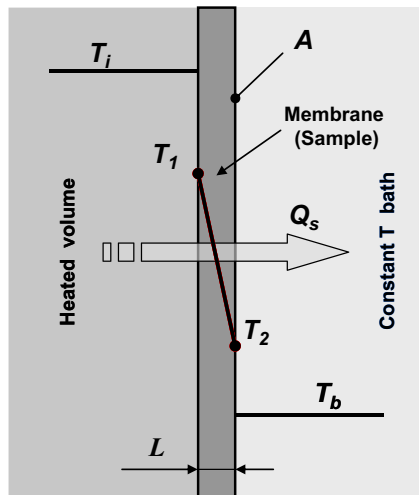


Fig. 1 Drum method scheme

In the considered case, the heat Q_s is transferred between the separated volumes by Kapitza conductance from the heated volume to one surface of the sample. It then goes through the sample material via heat conduction, and then via Kapitza conductance from the second sample surface to the isothermal (constant T_b) volume. This may be expressed as follows:

$$\frac{Q_s}{A} = h_k(T_i) \cdot (T_i^n - T_1^n) = \frac{k}{L} (T_1 - T_2) = h_k(T_b) \cdot (T_2^n - T_b^n) \quad (1)$$

where h_k is the Kapitza coefficient [$\text{W}/\text{m}^2 \text{K}^n$], and n is the dimensionless Kapitza heat transfer exponent, while k is the heat conduction coefficient of the sample material [W/mK], and T_1 and T_2 [K] are the temperatures of the sample surface

from the heated volume and the isothermal volume side, respectively.

For very small temperature differences between the separated volumes ($T_i - T_b = \Delta T \ll T_b$), the Kapitza conductance can be linearized, and (1) can be written in the following form:

$$\begin{aligned} \frac{Q_s}{A} &= n \cdot h_k(T_i) \cdot T_i^{n-1} (T_i - T_1) = \frac{k}{L} (T_1 - T_2) \\ &= n \cdot h_k(T_b) \cdot T_b^{n-1} (T_2 - T_b) \end{aligned} \quad (2)$$

As $\Delta T \ll T_b$, it can be considered that $T_i \approx T_b$, and:

$$\begin{aligned} R_s &= \frac{A \cdot \Delta T}{Q_s} = \frac{1}{n \cdot h_k(T_i) \cdot T_i^{n-1}} + \frac{L}{k} + \frac{1}{n \cdot h_k(T_b) \cdot T_b^{n-1}} \\ &= \frac{2}{n \cdot h_k \cdot T_b^{n-1}} + \frac{L}{k} = 2R_K + R_C \end{aligned} \quad (3)$$

where R_s [$\text{m}^2 \text{K}/\text{W}$], is the total thermal resistance of the heat transfer through the tested sample. It can be found from (3) that for small ΔT , the total thermal resistance is the sum of twice the Kapitza resistance R_K and the solid conduction resistance R_C .

2.2 The Sample Holder

The sample holder (see the schematic construction in Fig. 2) consists of a central flange and two sets of sample and compression flanges screwed to each side of the central flange. All flanges are made of stainless steel. Inside the central flange, an electrical heater (ceramic resistor) and a temperature sensor are located. The sample is glued, with the help of 3M DP190 Scotch-Weld Epoxy Adhesive, to the sample flange. The glued area is pressed, as required, by the compression flange during the drying of the epoxy.

Fig. 2 Drum method sample holder design scheme

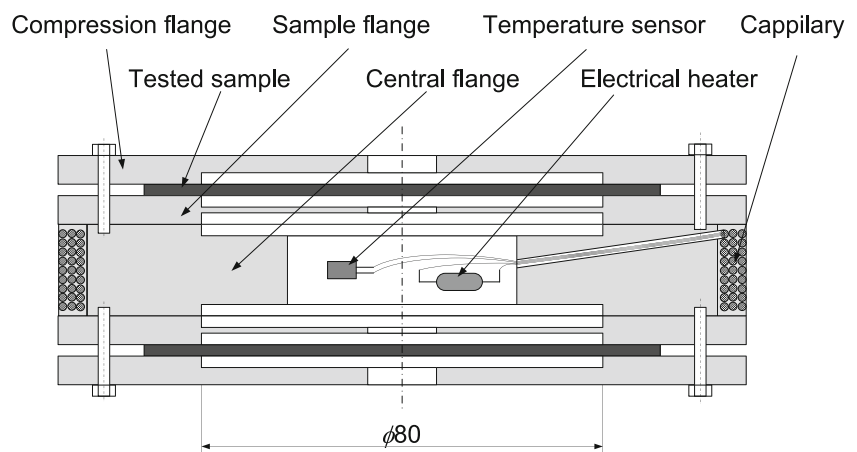
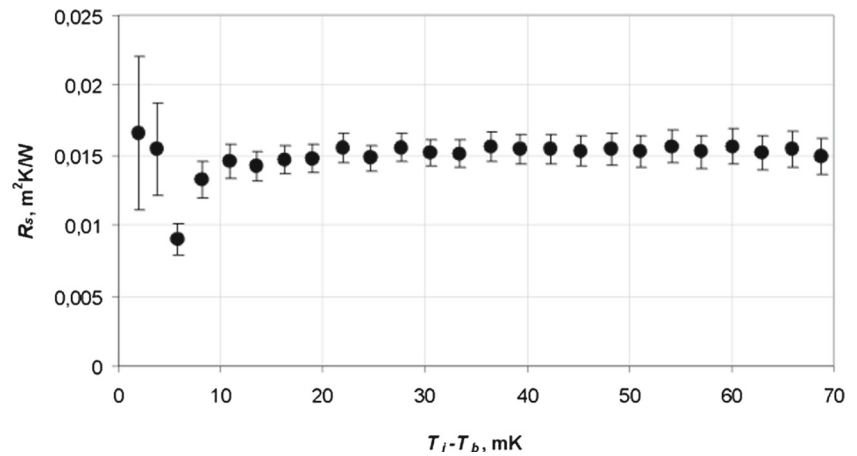


Fig. 3 Total thermal resistance R_s in function of ΔT for sample thickness 0.145 mm. $T_b = 1.7$ K



The active heat transfer area of the sample is limited by an 80-mm diameter circle. Two separate samples with this same thickness are installed on the central flange at once. The assembled holder creates the heated (inner) volume of the drum method, limited by the tested material and the central flange material. This volume is filled with HeIIp from the surrounded bath (isothermal volume of the drum method) with the help of a 500-mm long capillary with a 0.75-mm inner diameter, which ensures the minimization of heat loss due to heat conduction through the HeIIp. The capillary also carries 12 0.2-mm diameter instrumentation wires, four for the temperature sensor, four for the heater, and four for spear wires, which create a further limitation in area for HeIIp heat conduction.

2.3 Test and Data Fitting Procedure

In order to determine the Kapitza resistance and thermal conductivity of the tested materials, a superfluid helium cryostat from the Wrocław University of Technology was used. Three different thicknesses of the LARP material sheet were tested: 145 ± 7 , 250 ± 6 , and 367 ± 11 μm . The sample holders were placed inside the cryostat measurement vessel, where the HeIIp bath temperature (T_b) was controlled at a constant level. The total T_b error, accounting for the electronic readout and sensor-characteristic fitting errors, is assumed as ± 1.0 mK, while the T_b stabilization was better than ± 0.25 mK. Materials were tested at seven different T_b levels in the range of 1.5–2.0 K. At the given bath temperature, heat Q dissipated

Fig. 4 Total error of R_s value in function of the ΔT

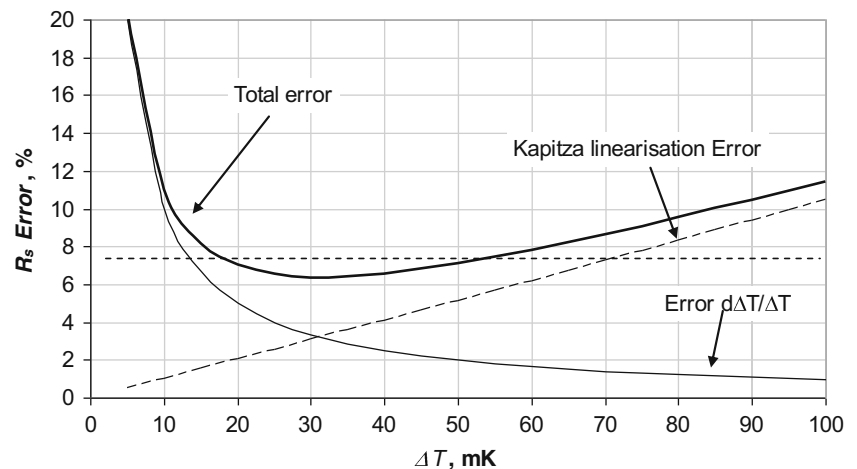
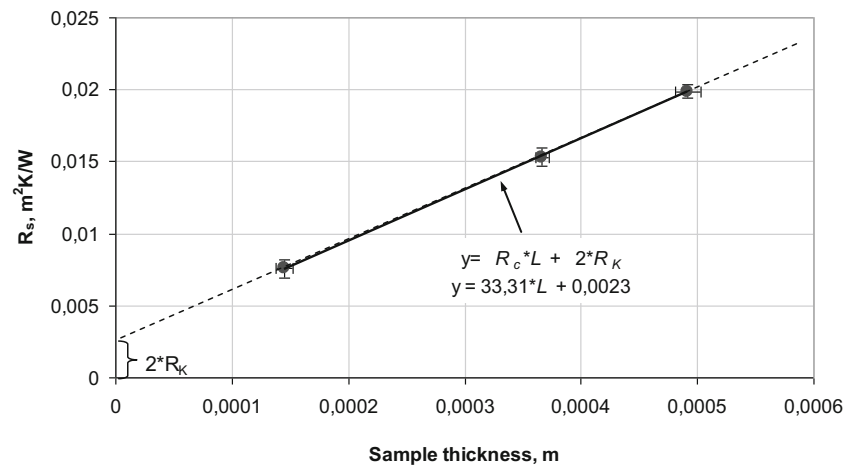


Fig. 5 Total thermal resistance in function of the sample thickness at $T_b = 1.7$ K



inside each holder in a range of 0–70 mW with a 2-mW ramp. The heat was generated with the use of the KEITHLEY 2400 source meter with an accuracy better than 0.1 % of the heat value. The temperature of the inner volume T_i was recorded in steady state conditions (T_i stabilization better than 0.25 mK) at a given value of Q . The total error for the ΔT value, determined as T_i at $Q = 0$ and T_i at the given Q value, can be assumed as ± 0.5 mK.

The Q transferred from the sample holder inner volume to the HeII bath is the sum of the heat transferred through the sample material Q_s , through the holder material Q_{hold} and through the capillary Q_{cap} . The Q_{hold} calculations, performed with the FE method, show that it varies from 2.5 % of Q for 145- μm thick sample to 4.5 % of Q for 367 μm . The capillary heat loss was calculated for each ΔT value and accounted for in further analysis with an assumed precision of ± 20 %, as an exact capillary cross-section area for helium conductance is difficult to determine.

Figure 3 presents an exemplary plot of the total thermal resistance R_s values in function of ΔT , where the R_s is calculated in accordance to (4). A detailed analysis of the total error composition shows that it is dominated by ΔT error, as well as error resulting from the linearization of the (1), which can be found from (4):

$$\varepsilon_{\text{Lin}} = 1 + \frac{3}{2} \frac{\Delta T}{T_i} + \left(\frac{\Delta T}{T_i} \right)^2 + \frac{1}{4} \left(\frac{\Delta T}{T_i} \right)^3 \quad (4)$$

The sum of the remaining errors is comparatively small and can be considered to be systematic error. As seen from Figs. 3 and 4, the R_s error value is large for $\Delta T < 15$ mK and for $\Delta T > 80$ mK. In order to minimize total error, the average value of R_s with the average R_s error values from the range of 20 mK $> \Delta T$ 50 mK is taken for further analysis.

The next step of the analysis is the preparation of the R_s -sample thickness graph for the given T_b level—see Fig. 5. In this graph, R_s points, fitting the line slope, stand for

Fig. 6 Thermal conductivity variation with temperature

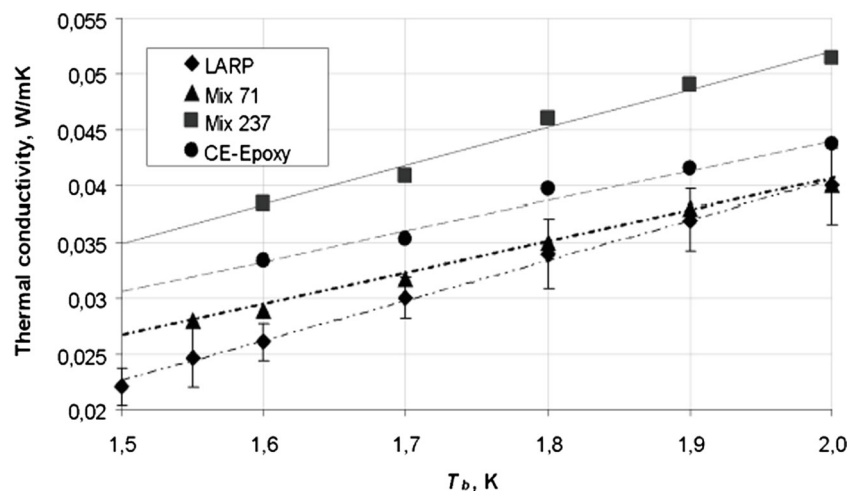
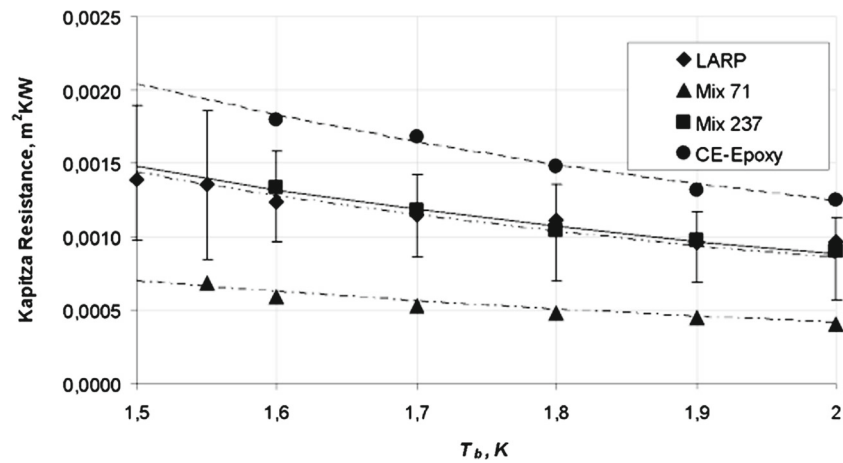


Fig. 7 Kapitza resistance variation with temperature



thermal conductance resistance R_c , while the intersection of the fitting line and R_s axis determines the double Kapitza resistance R_K value—compare with (3).

3 Results and Discussion

In Figs. 6 and 7, thermal conductivity and the Kapitza resistance value in the function of T_b in comparison with data obtained for Mix 71, Mix 237, and CE-epoxy materials are presented. It can be found that the LARP material is characterized by the lowest thermal conductivity: 25–35 % lower than Mix 237 and 10–30 % lower than CE-epoxy. On the other hand, the Kapitza resistance is very similar to the value for Mix 237 but 25 % lower than for CE-epoxy.

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